

University of Dundee

The disparate histories of binocular vision and binaural hearing

Wade, Nicholas J.

Published in:
Journal of the History of the Neurosciences

DOI:
[10.1080/0964704X.2017.1347389](https://doi.org/10.1080/0964704X.2017.1347389)

Publication date:
2018

Document Version
Peer reviewed version

[Link to publication in Discovery Research Portal](#)

Citation for published version (APA):
Wade, N. J. (2018). The disparate histories of binocular vision and binaural hearing. *Journal of the History of the Neurosciences*, 27(1), 10-35. <https://doi.org/10.1080/0964704X.2017.1347389>

General rights

Copyright and moral rights for the publications made accessible in Discovery Research Portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

- Users may download and print one copy of any publication from Discovery Research Portal for the purpose of private study or research.
- You may not further distribute the material or use it for any profit-making activity or commercial gain.
- You may freely distribute the URL identifying the publication in the public portal.

Take down policy

If you believe that this document breaches copyright please contact us providing details, and we will remove access to the work immediately and investigate your claim.

The disparate histories of binocular vision and binaural hearing

Running head: Binocular vision and binaural hearing

Nicholas J. Wade,
Psychology,
University of Dundee,
Nethergate,
Dundee DD1 4HN,
UK

Tel: +44 1382384616

E-mail: n.j.wade@dundee.ac.uk

This is the accepted manuscript version. The final published version is available via
DOI: 10.1080/0964704X.2017.1347389

Abstract

Vision and hearing are dependent on disparities of spatial patterns received by two eyes and on time and intensity differences to two ears. However, the experiences of a single world have masked attention to these disparities. While eyes and ears are paired there has not been parity in the attention directed to their functioning. Phenomena involving binocular vision were commented upon since antiquity whereas those about binaural hearing are much more recent. This history is compared with respect to the experimental manipulations of dichoptic and dichotic stimuli and the instruments used to stimulate the paired organs. Binocular color mixing led to studies of binaural hearing and direction and distance in visual localization were analyzed before those for auditory localization. Experimental investigations began in the 19th century with the invention of instruments like the stereoscope and pseudoscope, soon to be followed by their binaural equivalents, the stethophone and pseudophone.

Keywords binocular vision, binaural hearing, spatial localization, binocular and binaural instruments, dichoptic, dichotic

Introduction

The sense organs for seeing and hearing are paired but there has not been parity in the research devoted to them. The unity of perceptual experience has masked attention to differences in the stimuli available to two eyes and two ears and to the ways in which they are processed. Investigations over many centuries into seeing and hearing generally have favored the former. History has been kinder to vision than to hearing, if kindness is measured by the pages devoted to it throughout the ages in texts on the senses (see table 1). Contrasts between seeing and hearing can be considered in terms of the amount of space devoted to each in books on the senses. For example, in surveys of Greek theories more than twice the space is given to vision than hearing (Beare, 1906; Stratton, 1917) and the bias to vision was even greater for Galen (Siegel, 1970). Hearing did not fare any better in the medieval period (Kemp, 1990; Woolgar, 2006). The situation was little changed over the next four centuries. In his book on the nervous system and the senses, C. Bell (1803) devoted almost twice as many pages to vision as to hearing. A wider range of auditory phenomena was given by Boring (1942) in his book on the senses but the disparity was maintained. By the late 20th century the bias in favor of vision had increased (Barlow & Mollon, 1982; Held et al, 1978). More recently, the ratio of pages on vision to hearing was 3:1 in Goldstein (2010); the ratio was smaller for Kandel et al. (2013) but this was because some chapters devoted to vision in earlier editions were omitted.

Table 1 about here

Galileo was the exception to this trend (Piccolino & Wade, 2014; Wade, 2007). In expanding on the relation of stimulus to sensation in *Il Saggiatore*, Galileo (1623) devoted more attention to the senses of hearing, taste, smell and touch than to vision. Touch, taste,

smell and hearing were related to the elements of earth, water, fire and air. The analysis of these four senses was mechanical, both in terms of the stimulus and the response to it. Essentially, Galileo was following the Aristotelian path of treating touch, a patently mechanical sense, as the yardstick against which taste, smell and hearing should be considered. By contrast, Galileo was much more enigmatic in his consideration of vision:

And as these four senses are related to the four elements, so I believe that vision, the sense eminent above all others in the proportion of the finite to the infinite, the temporal to the instantaneous, the quantitative to the indivisible, the illuminated to the obscure – that vision, I say, is related to light itself. But of this sensation and the things pertaining to it I pretend to understand but little, and since even a long time would not suffice to explain that trifle, or even to hint at an explanation, I pass this over in silence. (Galileo, 1623/ Drake, 1957, p. 277)

The situations with regard to light and sound were succinctly summarised around the end of the 18th century. Joseph Priestley (1733-1804) in his survey of light and colors stated: “The phenomena of light and vision could not pass wholly unnoticed by those who gave the least attention to the works of nature, especially if they had any desire to know the cause of appearances, and the manner in which they are produced.” (1772, p. 1). After reviewing research on vision, C. Bell (1803) said of hearing: “When aerial undulations were, by the experiments on the air pump, first proved to be the cause of sounds, philosophers looked no further to the structure of the ear than to discover an apparatus adapted to the reception of such vibrations. When they observed the structure of the membrane of the tympanum, and its admirable capacity for receiving these motions of atmosphere, they were satisfied, without considering the immediate objects of sensation” (p. 440). That is, vision was concerned with

observations of phenomena while hearing was confined to the stimulus and the anatomy of the organ that responded to it. In one of the earliest books dedicated to the ear and hearing Du Verney (1683, 1737) lamented the state of studies of that sense:

Of all the Organs assign'd to the Use of Animals, we have the least Knowledge of those of the Senses; but there is none more obscure than that of Hearing: the Minuteness and Delicacy of the Parts which compose it, being inclos'd by other Parts, (which by reason of their Hardness, are scarcely penetrable) render the Enquiries into them more difficult, and their Structure something so intricate, that there is as much Trouble in explaining, as there is in discovering them. (Du Verney, 1737, p. vii)

Note that Du Verney directs his comments to studies of the anatomy of the inner ear rather than to the phenomena of hearing. Unlike equivalent books on vision of the period (like Le Clerc, 1679, and Molyneux, 1692, where binocular phenomena are discussed) there is no mention of hearing with two ears in Du Verney's book.

The question to ask is: why has vision been so favoured? It could relate to the knowledge about the stimulus for hearing (sound) in contrast to the ignorance about the nature of light. One consequence of this is that the study of vision was observational (and psychological) whereas that for audition was essentially physical. Additional factors relate to the sense organs themselves: the eyes can move, often in opposite directions, whereas the ears (in humans) require movements of the head to change their direction. Moreover, theories of vision have incorporated concepts concerned with spatial images for which there was no equivalent in audition. Binocular single vision has been a constant concern and it was integrated with stereoscopic depth perception in the early 19th century; investigations of binaural hearing followed closely thereafter.

Vision has been dominated by cataloguing observations whereas hearing has focussed on defining the stimulus – sound. The physical characteristics of sound were appreciated long before those of light. Sounds were produced by vibrating bodies and details of such vibrations were elaborated over centuries (Burnett, Fend & Gouk, 1991). The nature of light was much more enigmatic; for some it had its origin in the eye itself whereas others adopted more general interpretations regarding its origin. Thus, seeing and hearing were distinguished by knowledge of the sources of stimulation as well as by the concepts used to account for their reception. Most theories about the senses advanced by Greek thinkers and repeated over many centuries, incorporated elemental philosophy - fire, earth, water, and air permeated perception (Park, 1997). Touch was often taken as the most important sense, and the one relative to which others could be related; qualities associated with it, like hot, cold, moist, and dry were thought to be common to all the senses, and were in turn linked to the four elements. Sound, which could be considered as mechanical, could be more readily accommodated within this schema than could light. Speculations regarding vision involved spatial images which resembled the objects perceived. Spatial dimensions could be measured and manipulated in pictorial stimuli. In addition, it was appreciated that what could be seen with one eye differed slightly from that seen by the other. Hearing, on the other hand, is temporal and concepts of images were not incorporated into theories. Differences in the sounds experienced by one ear were rarely compared to those in the other. Fractionating time into smaller intervals proved much more difficult than fractionating space. Moreover, temporal resolution in hearing was much more acute than in seeing with the opposite applying to spatial resolution.

Over this large timescale, very little was written about binaural hearing, in contrast to the wealth of binocular phenomena that was discussed and investigated experimentally. Things were to change fundamentally in the 19th century both in terms of the instruments that

can differentially stimulate two eyes or two ears and the manner in which the new phenomena were interpreted (see Wade and Ono, 2005). The divergent histories of seeing with two eyes and hearing with two ears are reflected in the times at which terminologies associated with them were introduced. This in turn relates to the instruments that were devised to stimulate the paired organs. Porta (1593) used the term ‘binis oculis’ (two eyes) as part of a chapter heading in his book *De Refractione* and Schyrleus de Rheita (1645) described a ‘binoculum telescopium’ (binocular telescope). Chérubin d’Orléans (1671, 1677) called his paired telescopes a ‘binocle’ and this term was adopted for many binocular telescopes in the 18th century. By contrast a ‘bin-aural stethoscope’ was not introduced until much later by Alison (1861) and experiments on ‘binaural audition’ were not undertaken until the 1870s. The formal appreciation that hearing with two ears differed from that with one was made by Steinhauser (1877, 1879):

The theory of Audition may be divided into two portions – that of Monaural Audition, or of hearing with one ear, and that of Binaural Audition, or of hearing with both ears. The former, already treated in every textbook of Physics, is concerned with the arrangement of the human ear, the function of its separate parts, and, lastly, how the ear is instrumental in the faculty of hearing. The second branch of the subject, which has never, to my knowledge, been yet developed, has to discuss the general question of hearing, with respect in particular to the circumstance that it is performed with two ears. It is concerned, further, in deciding what part binaural hearing plays in the various phenomena of hearing in general, and the various advantages thereby gained. (Steinhauser, 1879, pp. 181–182)

Comparisons between seeing with one or two eyes are ancient whereas those for one and two ears are relatively recent. It was long believed that vision with one eye was superior to that with two. The source of much subsequent comparison was driven by the theory of visual spirit: it was transmitted from the ventricles to one or two eyes, and thus was more concentrated in monocular viewing. This opinion was repeated over the following centuries, and it was held as late as the seventeenth century, when Bacon (1627) attributed the advantages of aiming with one eye to this cause. There were opposing voices; Ptolemy and Ibn al-Haytham or Alhazen provided evidence for the superiority of two eyes over one but there was no adequate theory to incorporate their observations (see Sabra, 1987; Wade, 1998).

Many statements were made about tasks that were more difficult to perform with one eye rather than two, or stimuli that were more difficult to see. Leonardo da Vinci's often quoted comparison between viewing a painting of a scene and the scene itself was an implicit contrast between vision with one eye or two: "A Painting, though conducted with the greatest Art and finished to the last Perfection, both with regard to its Contours, its Lights, its Shadows and its Colours, can never show a *Relievo* equal to that of Natural Objects, unless these be view'd at a Distance and with a single Eye" (1721, p. 178). It is most instructive because the concept of relief or depth is taken to be the distinguishing characteristic of binocular vision. Attention was directed to tasks that could be performed better with two eyes but experimental support for the benefits of two eyes had to await the invention of the stereoscope by Wheatstone (1838). Indeed, the term 'depth perception' became widely used thereafter; previously the third dimension in vision had been referred to as 'distance'.

Aguilonius (1613) introduced the term 'stereographic' for projection of three dimensional objects (like spheres) on to a flat plane. The appearance of three-dimensionality with suitably paired pictures was the reason Wheatstone (1838) called his invention a

“stereoscope, to indicate its property of representing solid figures” (p. 374). Thereafter stereoscopic depth perception based on retinal disparities could be distinguished from equivalent binocular stimulation. A. Bell (1880) was similarly concerned with the solidity of auditory space and described aspects of binaural hearing as ‘stereophonic’. Techniques for presenting different stimuli to each of the paired organs opened new experimental avenues in their study. With the recognition that two ears do work together, a new terminology for stimulating the paired organs emerged (Wade & Ono, 2005). They were given the labels ‘dichotic’ for binaural hearing and ‘dichoptic’ for binocular vision. The term ‘dichotic’ was coined by Stumpf (1916); it referred to the stimulation of each ear with a different sound. It was distinguished from the simultaneous stimulation of each ear with the same sound. The application of ‘dichoptic’ to the stereoscopic or haploscopic stimulation of the eyes followed the adoption of ‘dichotic’ in studies of binaural hearing.

Light

The properties of light - how it is propagated through different media, how it reflects from surfaces, and how it is refracted at the boundaries between media - have been studied for well over two thousand years (see Ronchi, 1970; Russell, 1996, 2010). The terms to describe them - optics, catoptrics (reflections), and dioptrics (refractions), that were introduced by Hero of Alexandria in the 1st century AD - are still in use. However, the nature of light remained a mystery and it was not distinguished from sight. In antiquity, vision was generally considered to involve some process of contact between the eye and objects and several means of achieving this contact were advanced (Beare, 1906; Stratton, 1917). These included various versions of emission or extramission theories, in which light originated in the eye and was projected from it. Reception or intromission theories, in which light travelled from objects to the eye, were also advanced, as were speculations incorporating aspects of

both emission and reception. Emission theories could have been founded on the experience of light when pressure is applied to the eye, and they are consistent with the cessation of sight when the eyes are closed. The concept of some copy of objects, carried through the air to the eye, was to have widespread and long lasting appeal, and it was referred to by many names, including eidola, simulacra, species, images. There was an obvious source of observational support for such a theory: the image of an object could be seen reflected from the eye of an observer. The science of optics and ocular anatomy remained relatively unchanged in the mediaeval period until Ibn al-Haytham's work was translated into Latin and awakened Western scholars to the physics of light, its mathematical treatment, and its application to vision (Lindberg, 1976; Russell, 1996; Sabra, 1989). Physical optics came of age in the 17th century. Kepler (1604) described how an image is formed in the eye and later wrote a text on dioptrics (Kepler, 1611). Ocular anatomy was advanced by Scheiner (1619) who dissected the eyes of many mammals and provided an accurate representation of the gross anatomy of the eye. A century later, Newton (1704) presented a mechanistic interpretation of light and colors. With the appreciation that light could be considered as a physical property, and that its reflections and refractions followed physical principles, its study became the province of physicists, whereas the examination of sight was pursued by physiologists and philosophers. The separation of the physics of light from the philosophy of sight was to reflect the ancient schism between materialists and idealists: light was an external, material phenomenon whereas sight was internal and subjective (see Crombie, 1967).

Sound

In contrast to the wide range of theories about the nature of light, sounds could be produced by vibrating bodies like stretched skins or taut wires and such sounds could be investigated and related to the manner of hearing. It was in this context that Pythagoras in the 6th century

BC is said to have carried out investigations of the sounds produced by vibrating strings thereby relating sounds to his theory of numbers. Aristotle later argued that sound was transmitted through the medium of air by a process of displacement. Thus sounds could be analysed mathematically: “Acoustics, broadly defined to cover the nature of sound, was one of the earliest fields in the West or the East to be treated by exact measurement” (Carterette, 1978, p. 3). One consequence of this was to confine acoustics to physics rather than considering its psychological dimensions. When the psychological aspects of sound were examined it was usually in relation to music (Gouk, 1999, 2004).

More precise mathematical analysis of sound was made in the 17th century by Mersenne (1636) and Galileo (1638); they established that the pitch of a vibrating string is dependent on the frequency of its vibrations (Rayleigh, 1894). With regard to sound, Galileo adopted a mechanistic interpretation:

Then there remains the air itself, and element available for sounds, which come to us indifferently from below, above, and all sides – for we reside in the air and its movements displace it equally in all directions. The location of the ear is most fittingly accommodated to all positions in space. Sounds are made and heard by us when the air – without any special property of ‘sonority’ or ‘trasonority’ – is ruffled by a rapid tremor into very minute waves and moves certain cartilages of a tympanum in our ear. External means capable of thus ruffling the air are very numerous, but for the most part they may be reduced to the trembling of some body which pushes the air and disturbs it. Waves are propagated very rapidly in this way, and high tones are produced by frequent waves and low tones by sparse ones. (Galileo, 1623/Drake, 1957, p. 276)

The analogy between waves in water and sound waves in air proved persuasive both for sound and theories of light (Wade, 2005). In the 18th and 19th centuries, corpuscular theories of light were challenged by phenomena that conformed more closely to the action of waves rather than particles. Sound was analysed in terms of waves and a similar approach was suggested for light. For example, Grimaldi (1665) added diffraction to the direct propagation of light, its reflection and refraction; he also likened light to wave motion. In his book on light published two years after his death, he wrote: “Light can be considered analogous to a liquid which can also spread out in waves, namely, when it passes round an object” (Grimaldi, 1665/Mach, 1926, p. 134). Grimaldi demonstrated the phenomenon of diffraction by partially blocking sunlight passing through two small apertures: bands of color could be seen in the shadow area.

Young (1801, 1807) had been fascinated by the nature of sound and light since his studies as a student and he was an advocate of wave theory. His first article was concerned with accommodation (Young, 1793), a topic to which he returned in support of his hypothesis that the lens changed in curvature when focussing on objects at different distances. Throughout this period he was involved in a wide variety of studies on sound, and was particularly attracted to the acoustic figures described by Chladni (1802). The study of acoustic figures, also called Chladni figures, amplified the links between the stimuli for hearing and vision by providing an analysis of sound in spatial terms. Theories of vision have been framed in terms of ‘images’ – some spatial representation of the object perceived. It is easier to apply spatial than temporal metaphors to the senses and Chladni figures assisted in this. It could well be asked if there is an equivalent to ‘image’ in hearing.

Seeing with two eyes

The distinctions between the histories of light and sight and those of sound and hearing remain with regard to research on seeing with two eyes and hearing with two ears. However, in this instance understanding how the eyes work together provided the impetus for examining integration of signals from the ears. The advantages of having two eyes were recorded long before those for two ears were appreciated. This is reflected in the experimental studies that were undertaken to examine seeing and hearing, not to mention the contrivances that were invented to stimulate two eyes or two ears. The historical research on binocular vision has been enormous, but the same does not seem to apply to binaural hearing. There are marked differences in how we can compare perception with one or two organs. It is easy to close one eye and examine monocular vision but it is very difficult to ‘close’ one ear and study monaural hearing. Moreover, we can move our eyes either in the same direction (version) or in opposite directions (vergence) but humans have no equivalent means of moving the ears.

Many of the statements about binocular double vision are reflections of the breakdown of binocular single vision either by gently pushing one eye with the finger or as a consequence of strabismus; it often accompanied drunkenness, too. In his first article on stereoscopic vision, Wheatstone noted that “No question relating to vision has been so much debated as the cause of the single appearance of objects seen by both eyes” (1838, p. 387). Binocular single vision has been a source of experimental interest for over two thousand years (Howard & Rogers, 2012) but the same does not apply to binaural single audition – if the term has been used. Moreover, double vision can be induced experimentally, by presenting different stimuli to each eye. A variety of means of achieving this were available before the invention of the stereoscope (Wade and Ngo, 2013; Wade and Ono, 2012). For example, a range of methods was applied to the study of binocular vision in the 17th and 18th centuries. One (Figure 1), illustrated in the *Optics* of Aguilonius (1613), is attributed to

Rubens (Jaeger, 1990; Ziggelaar, 1983). The essence of investigating binocular vision was distilled from the methods adopted for stimulating the two eyes. The engraving by Rubens demonstrated the technique of fixating on one object located further from the eyes than another. This method was introduced by Ptolemy (Smith, 1996), and elaborated by Alhazen (1572; Sabra, 1989), before its widespread adoption in the seventeenth and eighteenth centuries. Another technique involved placing a septum between the eyes, so that peripheral objects could be seen by one eye but not the other. Galen described this method, and it was pursued by Porta (1593) and Aguilonius (1613) who took radically different positions regarding binocular vision. Porta maintained that we see with only one eye at once and he provided evidence for this from binocular rivalry. Viewing different pages of a book with different eyes resulted in reading one alone. This led to interest in eye dominance and Porta introduced tests for both sighting and rivalry dominance, which were assigned to the right side. He wrote: “Nature has given us two eyes, one on the right and the other on the left, so that if we are to see something on the right we use the right eye, and on the left the left eye. It follows that we always see with one eye, even if we think both are open and that we see with both” (Porta, 1593, p.143). Aguilonius, on the other hand, proposed that the two eyes worked together: “Whatever body, therefore, each eye sees with the eyes conjoined, the common sense makes a single notion, not composed of the two which belong to each eye, but belonging and accommodated to the imaginative faculty to which it (the common sense) assigns it” (Aguilonius, 1613, translated in Brewster, 1856, p. 13). The distinction between suppression and fusion theories of binocular single vision was heralded by these statements.

Figure 1 about here

Observing distant objects through a small aperture, so positioned that they are aligned each with one eye, was used by Le Clerc (1712) and Desaguliers (1716) to examine binocular combination whereas Du Tour (1760) placed shapes or patterns on different sides of a septum (Figure 2). However, the overriding interest was not in binocular depth perception but in examining binocular single vision and binocular rivalry.

Figure 2 about here

In the 19th century, the issue of single and double vision became the primary focus particular after Wheatstone's invention of the stereoscope. Both Vieth (1818) and Müller (1826) concluded on geometrical grounds that a stimulus on the circumference of a circle that passes through the two eyes and the intersection of the two visual axes leads to single vision. Countering the claim that single vision is limited to a stimulus on the circle (thereby stimulating corresponding points on the two eyes) Wheatstone (1838) found that a stimulus that falls on non-corresponding parts of the two eyes can be seen as single.

In the context of experiments on binocular single vision, Desaguliers (1716) devised a method of combining different stimuli in the two eyes that was to become widely employed in other studies of binocular vision, namely, placing an aperture in such a position that two more distant, adjacent objects were in the optical axes of each eye (see Figure 2). Desaguliers used the method to examine both binocular single vision and binocular color combination. Following Newton's experiments on color mixing, the combination of different colors presented to corresponding regions of each retina became an issue of theoretical importance. Indeed, it was Desaguliers (1716), an advocate of Newtonian optics, who was amongst the first to draw attention to the phenomenon. In particular, he showed that dichoptically presented colored lights rival rather than combine as in Newton's experiments on color

mixing. Using the same experimental apparatus as he employed for his studies of binocular single vision, he replaced the candles with patches of different colored silks and observed that color mixing did not occur. Moreover, if the colored patches were made more intense, the rivalry was more compelling; no color combination took place dichoptically, and the binocular rivalry between colors is more evident with intense stimuli. Desaguliers's method was applied by Taylor (1738), who added the refinement of placing colored glasses in front of candle flames; he found that colors combined rather than engaged in rivalry. Du Tour (1760) provided a clear description of binocular color rivalry. He achieved dichoptic combination by another means: he placed a board between his eyes and attached blue and yellow fabric in equivalent positions on each side, or the fabric was placed in front of the fixation point. When he converged his eyes to look at them they did not mix but alternated in color. Du Tour also applied the method of observing the colors through an aperture, as adopted by Desaguliers, and obtained similar results. Yet another technique was to view different colored objects through two long tubes, one in each optic axis. This method was used by Reid (1764), and he saw the colors combined although his description was not without its ambiguity: the colors were not only said to be combined, but also one "spread over the other, without hiding it" (p. 326). Venturi (1796, 1802), who conducted experiments on auditory localization, compared the combination of sounds to two ears with that of colors presented to different eyes. He placed blue and yellow papers next to one another on a table and over-converged his eyes to combine them: "I have repeated this experiment often and with care, and I have never experienced a third color from the two overlapping colors" (Venturi, 1802, p. 389). This was taken to be evidence that the nerves from the two eyes do not combine in the brain.

Dichoptic color combination could be examined with greater ease after the stereoscope had been invented: different colored patches could be placed on the separate

arms of the stereoscope so that the ensuing experience could be reported. Wheatstone (1838) found that blue and yellow discs engaged in rivalry rather than combination. After over one hundred fifty years of research it is evident that whether mixture or rivalry occurs depends on many factors such as luminance, saturation, stimulus duration and color difference. The physiological mechanisms underlying either mixture or rivalry are still unclear (Blake, 2002; Blake & Logothetis, 2002; Howard & Rogers, 2012).

Hearing with two ears

It was in the context of dichoptic color mixing that Wells (1792) suggested a thought experiment to link binaural hearing with binocular vision. It was based on Du Tour's (1760) dichoptic experiment described above:

From the fact of the two colors being thus perceived distinct from each other, I would infer, by analogy, a mode of argument indeed often fallacious, that if it were possible for us to hear any one sound with one ear only, and another sound with the other ear only, such sounds would in no case coalesce either wholly or in part, as two sounds frequently do, when heard at the same time by one ear; that consequently, if the sounds of one musical instrument were to be heard by one ear only, and those of another, by the other ear only, we could have little or no perception of harmony from such sounds; and that, if any succession of sounds emitted by one instrument, we were to hear the 1st, 3d, 5th, and so on, by one ear only, and the 2d, 4th, 6th, and so on, by the other ear only, we should be deprived, in a considerable degree, of the melody of such sounds, as this seems to depend in a great measure upon a new impression being made upon the auditory nerve by one sound, before the impression of the sound immediately preceding has passed away. (Wells, 1792, p. 46)

This probably constitutes one of the earliest considerations of examining dichotic listening experimentally, although Wells did not conduct such an experiment. Thus, the stimulus for examining dichotic listening derived from studies of dichoptic color perception.

Wheatstone was led to the study of vision through the visual expression of acoustic phenomena. Indeed, his first scientific paper was on acoustical figures (Wheatstone, 1823). His early experiments were addressed to Chladni figures and a range of other auditory phenomena (Wheatstone, 1823, 1827, 1833). He also reported that the normal combination of two different sounds to yield a third sound did not occur if the two sounds were presented separately to the two ears:

Select two tuning-forks the sounds of which differ by any consonant interval excepting the octave: place the broad sides of their branches, while in vibration, close to one ear, in such a manner that they shall nearly touch at the acoustic axis; the resulting grave harmonic will then be strongly audible, combined with the two other sounds; place afterwards one fork to each ear, and the consonance will be heard much richer in volume, but no audible indications whatever of the third sound will be perceived. (Wheatstone, 1827, p. 71)

That is, beats were heard when two tuning forks were close to one ear but not when they were close to separate ears. The study of binaural beats is usually attributed to Dove (1839) despite the fact that he cited Wheatstone in his paper. It was binocular color mixing that led Dove (1841) to compare vision and hearing with paired organs. He demonstrated that stereoscopic pairs were seen in depth even when illuminated by an electric spark, thereby excluding the occurrence of eye movements during observation. Dove sounded different tuning forks to

each ear and noted that they combined, unlike the case with dichoptic color mixing. The opposite outcome was reported by Seebeck (1846), who used sirens as well as tuning forks. He found that binaural sounds as well as binocular colors combined. Weber (1846) was similarly stimulated to examine an aspect of binaural hearing on the basis of his belief that two different binocular stimuli could not be perceived simultaneously. Fechner (1860) also compared binocular single vision, based on stimulating corresponding retinal points, with binaural single hearing. However, Fechner's observations were directed to the effects of attention on discrimination. Whereas he was unable to distinguish between the sounds of two watches held next to one ear, when they were placed before separate ears they could not only be distinguished, but he could hear first one then the other. He likened this to rivalry between the ears. Unlike binocular rivalry, binaural rivalry involved shifts of location as well as perception.

Thus, it was several decades after Wells' (1792) 'thought experiment' that interest in binaural combination was again aroused, although his thoughts were not cited. In addition to the studies by Wheatstone (1827), Dove (1841), Seebeck (1846), Weber (1846) and Fechner (1860), Thompson (1877) conducted an experiment rather like that suggested by Wells: he produced beats binaurally by sounding tuning forks in each ear independently. He also noted that the apparent location of the sound was at the back of the head when the vibrations were out of phase. This was followed up by a second paper in which Thompson (1878) investigated the effects of pitch, phase, intensity, and quality on auditory localization.

Müller (1843) described a procedure that a century later became a standard method for examining dichotic listening:

When two persons address their speech to our opposite ears simultaneously, the two impressions conveyed to the sensorium become mixed; and it is only by great exertion

of the attention, and by the aid of a difference of tone of the two voices, that we are enabled to follow the sounds of one exclusively, disregarding those of the other, which are then heard as a more or less indistinct murmur. (Müller, 1843, pp. 1307–1308)

Müller appreciated that attention was required to follow one of the messages, and from the 1950s, dichotic listening tasks were examined in the context of selective attention (see Cherry, 1961; Yost, 1997). Cherry (1953) presented different messages to each ear and noted that one could be followed particularly if the person's name was mentioned; he called it the cocktail party phenomenon.

One area of closer parallel between dichoptic and dichotic studies is related to rivalry. Indeed, an earlier comparison between using two eyes and two ears arose in this context. Porta (1593) speculated about ear dominance as he had about eye dominance: "If we hear someone talking with the right ear we cannot listen to another with the left ear; and if we wish to hear both we shall hear neither, or indeed if we hear something with the right we lose the same amount from the left" (p. 143). Thus, interest in ear dominance arose from speculations about eye dominance. Porta (1593) introduced tests for both sighting and rivalry dominance, which were assigned to the right side, acuity dominance (favoring the left eye) was claimed by Borelli (1673). These conclusions were usually based on individual observation, and few attempts at comparisons between individuals were undertaken. Experimental investigations of ear dominance appeared much later than these reports. Coren (1992) stated: "Of all the aspects of sidedness, *earedness* has been the least well studied" (p. 31); incidence of right-eyedness is given as 70 % and right-earedness as 60 %.

Visual and auditory localization

Studies of binocular single vision can be traced back over two thousand years. They were implicitly concerned with visual localization but, after Ibn al-Haytham, they were related to projections to the eye (Russell, 1996). Specifying the locus between the eyes from which objects appeared to be aligned was to await the analyses of Wells (1792) and Hering (1879). The location of any point in space can be described by specifying its direction and distance, from the vantage point of an observer. Wells (1792) made the distinction between visual direction and visual distance explicit, but experimentally he examined visual direction and not distance. He hypothesized that visual direction is processed with an innate mechanism (by “nature”) and that visual distance is processed by an acquired mechanism (by “custom”). He demonstrated experimentally that the direction relative to which objects are seen lies between the eyes rather than in either eye. When Hering (1879) turned to visual direction Wells had been forgotten. Hering rediscovered the principles of visual direction described by Wells although no references were made to his work (Ono, 1981). Hering did introduce the concept of the cyclopean eye (Wade, 2003).

Since the invention of the stereoscope attention has again focused principally on perceived depth or distance. Wheatstone’s empiricist and psychological interpretation of binocular combination was supported by Helmholtz (1867). Partly because of this support, thereafter the consideration has been on perceived depth and distance, and most textbooks on perception discuss visual distance and depth but not visual direction. Nonetheless, visual direction and visual distance constitute a considerable portion of the study of binocular vision, and there exists a very large literature (see Blundell, 2011; Howard & Rogers, 2012).

Experimental investigations of auditory localization probably commenced with Venturi’s (1796, 1802) studies comparing listening with both ears or with one blocked by a

finger. A blindfolded listener stood on a flat and unbounded surface and notes from a flute were played from various directions at a distance of 40–50 meters. In his first study one ear was stopped by a finger. Sounds could be located when they were perpendicular to the open ear. This direction was called the auditory axis, following the concept of the visual axis. His second study was also with one ear stopped but the blindfolded listener turned until the sound was loudest. This occurred when the sound was in the auditory axis of the open ear. The third study was with both ears open and a stationary head. The listener was able to determine with reasonable accuracy the direction of a sound, but this could not be maintained when one ear was stopped with a finger. Partially blocking one ear changed the apparent direction of the sound. On the basis of this observation Venturi stated: “Therefore the inequality of the two impressions, which are perceived at the same time by both ears, determines the correct direction of the sound” (Venturi, 1802, p. 186). Venturi also established that a listener with both ears open could not distinguish between a sound directly in front of them or behind.

Almost 70 years after Venturi’s experiments, Lord Rayleigh (John William Strutt) performed a similar study, but in ignorance of its predecessor. Rather than move around a listener (because the footsteps could be detected), he placed assistants in several directions and they produced sounds when instructed: “The uniform result was that the direction of a human voice used in anything like a natural manner could be told with certainty from a single word, or even vowel, to within a few degrees” (Rayleigh, 1876, p. 32). Similar results were found with tuning forks, although sounds from directly ahead or behind were confused. Differences between the intensities of sounds at each ear were thought to be involved, but calculations of the differences led him to question whether they were large enough to account for the power of discrimination.

Steinhauser (1877, 1879) built his theory of binaural hearing on an analysis of auditory localization: “*the direction in which a source of sound is situated may be estimated*

by the different intensities with which a sound is perceived in the two ears” (1879, p. 186).

The pinna of each ear played a significant role in the differential intensities reaching the auditory canal, as he indicated graphically (Figure 3), and determined trigonometrically.

Sounds within the angle DnC were referred to as direct because they were projected to each ear whereas those within the angles AnD or BnD were called mixed due to the direct stimulation of one ear relative to the other; indirect stimulation was from behind the head. He divided the whole of auditory space into three regions: “*in front*, the region of direct hearing; *at the two sides*, the regions of mixed hearing; and *at the back*, the region of indirect hearing” (Steinhauser, 1879, p. 272).

A. Bell (1880) also performed an experiment similar to that of Venturi but with the added technical sophistication of the telephone. He was aware that “the difference between monaural and binaural audition is especially well marked when we attempt to decide by ear the locality of a particular sound” (Bell, 1880, p. 169). In order to pursue this difference experimentally he set up an arrangement of telephones receiving signals from one room and listened to in another (Figure 3). Telephone A was connected to C and B to D. They were separated by about the distance between the ears. A and B were in one room (EFGH) while C and D were in another. Speech from a person moving around room EFGH could be heard by the listener using either C and D or C or D alone. The listener was required to indicate the location within the room of the speaker. He concluded that “the direction of a source of sound is less perfect by a single ear than by both ears” (1880, p. 175). He also found, like Venturi and Lord Rayleigh, that binaural sounds could be localized in the auditory axis but that those from straight ahead or behind were confused.

Figure 3 about here

A. Bell's interests in binaural audition were influenced by Thompson's (1877, 1878, 1881) experiments on binaural beats. Thompson had used telephones in some of his lectures and corresponded with Bell about them (Thompson & Thompson, 1920). It was during a visit to London that Bell started to examine the phenomena of stereophonic hearing in a manner similar to that applied to stereoscopic vision:

There seems to be a one-sidedness about sounds received through a single ear, as there is about objects perceived by one eye. When both ears are employed simultaneously, a sort of stereoscopic effect of audition is perceived. Sounds assume a "solidity" (if I may use the expression) which was not perceptible so long as one ear alone was employed. The difference between monaural and binaural audition is especially well marked when we attempt to decide by ear the locality of a particular sound. (Bell, 1880, p. 169)

A. Bell went on to describe "that the stereophonic phenomena of binaural audition might be produced artificially by the telephone, in like manner as the peculiarities of binocular vision are produced by the stereoscope" (pp. 169-170). His experiments with paired independent telephone signals supported the superiority of binaural over monaural localization. Bell was also intrigued by Thompson's pseudophone about which they also corresponded.

Thompson (1882) examined auditory localization in the context of visual localization. Both were analyzed in terms of direction and distance (as Wells had advocated for vision over a century earlier), and Thompson noted the differences between ears and eyes in terms of focusing, receptor layout, and motor control. The features involved in auditory localization were listed:

There are four physical characteristics of waves of sound by which one sound is discriminated from another, viz:- (i) *Intensity*, or loudness, depending upon extent or energy of the vibratory motions. (ii) *Pitch*, or frequency, depending upon the rapidity of the vibratory motions. (iii) *Phase* of the vibratory motions, as to T whether moving backward or forward or at any other state. (iv) *Quality*, or timbre, depending upon the degree of complexity of the vibratory motion. The third of these physical characteristics is one for which the single ear possesses no direct means of perception. (Thompson, 1882, p. 408, original italics)

Thus, Thompson argued that phase differences alone were in the province of binaural hearing and so served the function of localizing the direction of sounds in space. Distance presented a more complex problem, and he considered that: “In the case of known sounds we doubtless judge chiefly of their distance by their relative loudness, the intensity decreasing inversely as the square of the distance” (1882, p. 415). Nonetheless, Thompson did entertain the possibility of ‘acoustic parallax’ playing a role in its determination for sounds at short distances.

Further study was inhibited by debates regarding absence of spatiality in hearing (see Boring, 1942). When auditory localization was examined at the end of the 19th century it was dominated by controversies over whether intensity or temporal differences serve as cues, but there were researchers also concerned with non-theoretical experimental questions (see Pierce, 1901). Rayleigh (1907) proposed a duplex theory of binaural localization: it was possible due to interaural differences in intensity and time of arrival of the sounds. Later it was recognized that the two bases for localization operated at different frequency bands; one for high frequency tone serving as an intensity cue and the other for low frequency tones serving as a temporal cue (von Hornbostel & Wertheimer, 1920). There now exists a large

body of binaural phenomena but they are based on relatively recent studies (see Wade & Deutsch, 2008).

Binocular instruments

A wide variety of binocular instruments had been devised before Wheatstone invented the stereoscope. One of the contenders as inventor of the telescope, Hans Lippershey, took out a patent for a binocular telescope in 1608 (Schmitz, 1982). At the beginning of the 17th century the theory that vision with one eye was superior to that with two was being questioned and a range of binocular instruments were produced in that century. For example, Schyrleus de Rheita (1645) described a binocular telescope as did Chérubin d'Orléans (1671, 1677, 1678) and Zahn (1686) – both of whom also illustrated binocular microscopes (Figure 4). The telescopes (called binocles) consisted of paired tubes with parallel instruments and they were constructed in the belief that vision with two eyes was superior to that with one. Chérubin d'Orléans wrote:

The two eyepieces of the binocle are placed in their own tubes in such a way that one can see distinctly through each separately, and they can be adjusted as required for the two visual axes, so that the two eyes, which are looking at the same time, each with its own view, together see just one and the same object. (1677, p. 73)

Chérubin d'Orléans also illustrated a binocular microscope (Figure 4) and described it as follows:

It is known how to construct a novel type of microscope, in order to see the smallest object very agreeably and conveniently, represented entirely to the two eyes together,

with a size and distinctness which surpasses all that we have seen until now with this type of microscope. (1677, p. 77)

The same principles were applied to telescopes and microscopes and Zahn's (1686) model is shown with a specimen on the viewing plate (Figure 4). The lower illustration is often attributed to Chérubin d'Orléans although his prints were steel engravings and not woodcuts. The attribution is likely to be due to Mayall (1886) who represented it with the legend 'Chérubin d'Orléans' binocular microscope (1678)' while stating in the text that the illustration was from Zahn (1685), although it was actually from Zahn (1686). Carpenter (1901) repeated the claim on Mayall's authority and reprinted Mayall's illustration with the same caption. The misattribution has been repeated many times since (e.g. Gregory, 1981) with deference to Carpenter's authority!

Figure 4 about here

There were questions about the advantages of a binocular microscope soon after Chérubin's book was published. In comparing monocular and binocular microscopes Hooke (1679) favored the former, remarking "that with one Eye only, which is much to be preferred before that with two" (p. 102). It is highly unlikely that these binocular microscopes would have afforded stereoscopic impressions of minute objects simply because of their construction. Wheatstone (1853) noted that the arrangement of the eyepieces was such that any effects would have been pseudoscopic rather than stereoscopic. That is, the disparities were reversed so that near parts of the specimen would have had uncrossed disparity whereas that for far parts would have been crossed. The early instruments were made without an adequate understanding of binocular disparities. Clear descriptions of retinal disparities were

introduced in the 17th century (Le Clerc, 1679) and they were commonplace in the 18th century (see Harris, 1775; Smith, 1738). However, the functions that such disparities served were not appreciated until Wheatstone (1838) demonstrated depth from disparity with his stereoscope.

While these instruments were binocular they were not stereoscopic, as Wheatstone (1853) pointed out:

In the Père d'Orléans' binocular microscope, two object-glasses have their lateral portions cut away so as to allow of close juxta-position, and these nearly semi-lenses are so arranged, that their axes correspond to the two optic axes passing through the tubes containing the eye-pieces. The author's aim in its construction was solely the reinforcement of the impression by presenting an image to each eye, for he assumes, according to the then prevalent error, that vision by the two organs conjointly is naturally and necessarily unique, from the perfect conformity of all the homonymous parts of the two images of the object on the two retinae. The real advantage of such an instrument entirely escaped his attention; viz., that of presenting to the two eyes the two *dissimilar* microscopic images of an object, under precisely the same circumstances as the two unlike images of any usual object is presented to them when no instrument is employed, by which simultaneous presentment the same accurate judgment as to its real solid form, and the relative distances of all its points, can be as readily determined in the former case as in the latter. (Wheatstone, 1853, p. 101)

Wheatstone tried to interest optical instrument makers to manufacture stereoscopic microscopes but was unsuccessful (see Wade, 1981). He did not pursue the endeavour because Riddell (1853) and Wenham (1854) described stereoscopic microscopes soon after.

Wheatstone invented the stereoscope in the early 1830s, and it opened a new world for the study of binocular vision. That world was the laboratory, and with the aid of the stereoscope the methods of physics could be applied to the investigation of spatial vision. Wheatstone made mirror and prism stereoscopes as early as 1832, but he only described the mirror version in his classic memoir of 1838 (Figure 5). Wheatstone described the mirror stereoscope at a meeting of the Royal Society of London in June, 1838 and he demonstrated the device to a meeting of the British Association for the Advancement of Science held at Newcastle in August, 1838. Wheatstone invented the stereoscope to establish the nature of binocular depth perception (Wade, 1983). With the aid of the instrument he was able to manipulate the pictures presented to each eye and to observe the depth that was produced. In so doing, he found that:

... the projection of two obviously dissimilar pictures on the two retinae when a single object is viewed, while the optic axes converge, must therefore be regarded as a new fact in the theory of vision. It being thus established that the mind perceives an object of three dimensions by means of the two dissimilar pictures projected by it on the two retinae, the following question occurs: What would be the visual effect of simultaneously presenting to each eye, instead of the object itself, its projection on a plane surface as it appears to that eye (Wheatstone, 1838, pp. 372-373).

Figure 5 about here

As discussed earlier, the geometry of retinal disparities was well known but such disparities were considered to lead to double vision rather than depth perception. The

stereoscope transformed the understanding of binocular vision and it spawned a variety of alternative ways of presenting different pictures to the eyes. The most popular model of stereoscope was Brewster's (1849b) lenticular version (Figure 5). It consisted of a single lens cut in half so that the two half-lenses, when appropriately mounted, acted as magnifiers as well as prisms, fusing adjacent stereo drawings or photographs. The first model was made by George Lowdon, an optical instrument maker in Dundee, but the version displayed at the Great Exhibition, held in Crystal Palace, London in 1851 was made by Louis Jules Duboscq of Paris (see Wade, 2016). It was more popular than the mirror stereoscope because it was more compact and could be used more conveniently with paired photographs. Brewster (1849a) also described a binocular camera but did not construct one. Benjamin Dancer made his first model in 1852 and he produced an improved, commercially available model in 1856 (Dancer, 1886). Dancer was an optical instrument maker in Manchester and added many refinements to binocular cameras, like variable apertures for the lenses, a ratchet system for advancing unexposed dry plates and a spirit level to assist in the appropriate alignment of the two lenses.

Wheatstone's (1852) second article on binocular vision was published fourteen years later. He described and illustrated an adjustable mirror stereoscope, a prism stereoscope, and a pseudoscope for reversing disparities. The main purpose of these was to extend the range of conditions under which the two eyes could be stimulated. Wheatstone (1852) used the stereoscope with adjustable arms to vary the four circumstances mentioned in the quotation (retinal size, convergence, accommodation, and disparity). He applied the pseudoscope to reverse the normal relations between monocular and stereoscopic cues to depth: "With the pseudoscope we have a glance, as it were, into another visible world, in which external objects and our internal perceptions have no longer their habitual relation with each other" (p.

12). He remarked on the difficulty of perceiving reversals of relief with the pseudoscope, and the illuminating conditions that are necessary for such reversal.

Wheatstone was well aware of the fact that object recognition could influence the depth perceived but he did not have any means of removing objects from the stereopairs. With the advent of computer generated images, Julesz (1971) realised Wheatstone's dream – he made random dots stereograms in which there was nothing presented to either eye alone that could indicate the depth to be seen. Only with their combination could the depth emerge in what he called cyclopean vision.

Binaural instruments

Perhaps the first binaural instrument was Wheatstone's (1827) microphone: it consisted of wires connected to metal plates that could be placed over each ear (Figure 6). He was trying to amplify weak sounds: "The greater intensity with which sound is transmitted by solid rods, at the same time that its diffusion is prevented, affords a ready means ... of constructing an instrument which, from its rendering audible the weakest sounds, may with propriety be named a Microphone" (Wheatstone, 1827, p. 69). Later in the nineteenth century the microphone was associated with the conversion of sound into electrical signals. However, it was not Wheatstone's stereoscope that stimulated others to examine binaural hearing, but his pseudoscope. His invention of the pseudoscope, which reversed retinal disparities, followed 14 years after the stereoscope had been made public (Wheatstone, 1852). The most popular model of stereoscope was Brewster's lenticular version, although he illustrated a wide variety of methods for combining stereopairs (Brewster, 1851), as did Dove (1851).

It was Wheatstone's pseudoscope that provided the incentive for Thompson (1879) to make a pseudophone (Figure 6) for hearing:

The Pseudophone is an instrument for investigating the laws of Binaural Audition by means of the illusions it produces in the acoustic perception of space. It is therefore the analogue for the ears of the Pseudoscope of Wheatstone, which serves to illustrate the laws of Binocular Vision by means of the illusions it produces in the optical projections... The simple instrument for which the author suggests the name Pseudophone consists of a pair of ear-pieces, A A, furnished with adjustable metallic flaps or reflectors of sound, C C, which can be fitted to the ears by proper straps, D and E, and can be set at any desired angle with respect to the axis of the ears, and can also be turned upon a revolving collar about that axis so as to reflect sounds into the ears from any desired direction. (Thompson, 1879, pp. 385 and 387)

Ear trumpets have long been in use: they were used as aids to hearing, akin to spectacles for assisting sight (Hunt, 1978), and they were mentioned in 17th century treatises on music (Gouk, 1999). Kircher (1673) illustrated several of them in his book on hearing. He also illustrated large tubes that were used for communication between different parts of a building. Both Hooke and Newton described ear trumpets as aids to hearing, and Hooke speculated that it should be possible to hear the internal movements of the body by means of a suitable instrument. It took many years before such specific auditory instruments were devised in the context of medicine. Laennec (1819) invented a simple tube that could amplify sounds from the chest when placed between ear and chest; it became called a stethoscope. The cylinder could be made of paper, but wood proved more durable. Laennec found that the sounds were louder with a cylinder than when the ear was applied directly to the chest; it also avoided embarrassment when examining female patients. Adapting a single tube which then connected to two ears appeared shortly afterwards, although its adaptation was more for convenience than for any binaural benefits: “It occurred to the writer that both ears might be

simultaneously and advantageously employed in stethoscopic examinations. The instrument adapted to this purpose consists of a tube, connected at its middle at right angles to the cylinder, to be applied to the patient, and connected at its moveable extremities to two tubes” (Comins, 1829, p. 430). Although instruments of this type were later referred to as bin-aural stethoscopes by Alison (1861), they were not stereophonic because the two ear tubes were connected to a single receiving tube.

The auditory equivalent of the stereoscope was invented by Alison (1859) and it was called a stethophone (Figure 6). It consisted of independent ear tubes so that different sounds could be listened to:

The tubes are composed of two parts nearly equal in length, one near the ear-knob, made of metal (C); while the other part, near the collecting cup, is made of metal wire (B), to impart flexibility. The ear-end is curved, so as to approach the ear, and is supplied with an ivory knob (D) for insertion into the meatus externus. The other end of the tube, being intended to collect sound, is supplied with a hollow cup, or receiver (A) made of wood, or some such material. (Alison, 1859, pp.197-198).

Alison was not stimulated to study binaural hearing on the basis of Wheatstone’s stereoscope, but as a consequence of his experiments in audition. Alison’s experiments mostly involved two watches and he formulated two laws: “1st, that sounds of the same character are restricted to that ear into which they are conveyed in greater intensity, and 2nd, that sounds differing in character may be heard at the same time in the two ears respectively, even if they be made to reach the ears in different degrees of intensity” (Alison, 1859, p. 205).

Figure 6 about here

Conclusion

The study of vision has almost always been with regard to a spatial metaphor. Initially it was based on phenomenal distinctions, like visual directions. Later it was associated with corresponding points in the two retinas. Spatial disparities in either visual directions or corresponding points could be related to differences in visual perception. Temporal metaphors are not so amenable either to conceptualize or to experiment upon. Historically, it was more difficult to manipulate precisely the temporal characteristics of sound stimuli than the spatial aspects of light. Instruments for examining binaural hearing were generally invented later than those for binocular vision, and the names given to the former often derived from the latter.

References

- Aguilonius F (1613): *Opticorum Libri Sex. Philosophis juxta ac Mathematicis utiles*.
Antwerp, Moreti.
- Alhazen (1572): *Opticae Thesaurus*. Basel, Gallia.
- Alison SS (1859): On the differential stethophone, and some new phenomena observed with it. *Proceedings of the Royal Society of London* 9: 196–209.
- Alison SS (1861): The physical examination of the chest in pulmonary consumption and its intercurrent diseases. *British and Foreign Medico-Chirurgical Review* 28: 145–154.
- Aquapendente HF ab (1600): *De Visione , de Voce, de Auditu*. Venice, Bolzetti.
- Bacon F (1857): *Sylva Sylvarum: or A Natural History*. In: Spedding J, Ellis RL, & Heath DD, eds., *The Works of Francis Bacon*, Volume 2. London, Longman, Simpkin, Hamilton, Wittaker, Bain, Hodgson, Wasbourne, Bohn, Richardson, Houlston, Bickers and Bush, Willis and Sotheran, Cornish, Booth, and Snow.
- Barlow HB, Mollon JD (1982): *The Senses*. Cambridge, Cambridge University Press.
- Beare JI (1906): *Greek Theories of Elementary Cognition from Alcmaeon to Aristotle*.
Oxford, Clarendon Press.
- Bell AG (1880): Experiments relating to binaural audition. *American Journal of Otology* 2: 169-179.
- Bell C (1803): *The Anatomy of the Human Body*, Volume 3. London, Longman, Rees, Cadell and Davies.
- Blake R (2002): Reconciling rival interpretations of binocular rivalry. In: Harris L, Jenkin M, eds., *Levels of Perception: A Festschrift for Ian Howard*. (pp 101- 126). New York, Springer.
- Blake R, Logothetis NK (2002): Visual competition. *Nature Reviews Neuroscience* 3: 13- 21.
- Blundell BG (2011): *3D Displays and Spatial Interaction: Exploring the Science, Art,*

- Evolution and Use of 3D Technologies*. Auckland, New Zealand, Walker & Wood.
- Borelli A (1673): Observations touchant la force inégale des yeux. *Journal des Sçavans* 3: 291-294.
- Boring EG (1942): *Sensation and Perception in the History of Experimental Psychology*. New York, Appleton-Century.
- Brewster D (1844): On the knowledge of distance given by binocular vision. *Transactions of the Royal Society of Edinburgh* 15: 663-674.
- Brewster D (1849a): Description of a binocular camera. *Report of the British Association for the Advancement of Science. Transactions of the Sections*: 5.
- Brewster D (1849b): Account of a new stereoscope. *Report of the British Association for the Advancement of Science. Transactions of the Sections*: 6–7.
- Brewster D (1851): Description of several new and simple stereoscopes for exhibiting, as solids, one or more representations of them on a plane. *Transactions of the Royal Scottish Society of Arts* 3: 247–259.
- Brewster D (1856): *The Stereoscope: Its History, Theory, and Construction*. London, Murray.
- Burnett C, Fend M, Gouk P (Eds.) (1991): *The Second Sense: Studies in Hearing and Musical Judgement from Antiquity to the Seventeenth Century*. London, Warburg Institute.
- Carpenter WB (1901): *The Microscope and its Revelations*. 8th ed. London, Churchill.
- Carterette EC (1978): Some historical notes on research in hearing. In: Carterette EC, Friedman MP. eds., *Handbook of Perception. Volume 4. Hearing*. (pp 3-39). New York, Academic Press.
- Cherry C (1953): Some experiments on the recognition of speech, with one and two ears. *Journal of the Acoustical Society of America* 25: 975–979.
- Cherry, C. (1961): Two ears—but one world. In: Rosenblith WA. ed., *Sensory*

- Communication* (pp 99–117). Cambridge, MA, MIT Press.
- Chérubin d'Orléans (1671): *La Dioptrique Oculaire, ou la Theorique, la Positive, et la Mechanique, de l'Oculaire Dioptrique en toutes ses Espèces*. Paris, Jolly & Bernard.
- Chérubin d'Orléans (1677): *La Vision Parfaite: ou les Concours des deux Axes de la Vision en un seul Point de l'Objet*. Paris, Marbre-Cramoisy.
- Chérubin d'Orléans (1678): *De Visione Perfecta sive de amborum Visionis Axium Concursu in eodem Objecti Puncto*. Paris, Marbre-Cramoisy.
- Chladni EFF (1802): *Die Akustik*. Leipzig, Breitkopf und Härtel.
- Comins N (1829): New stethoscope. *London Medical Gazette* 4: 427-430.
- Coren S (1992): *The Left-Hander Syndrome. The Causes and Consequences of Left-Handedness*. New York, The Free Press.
- Crombie AC (1967): The mechanistic hypothesis and the scientific study of vision: Some optical ideas as a background to the invention of the microscope. In: Bradbury S, Turner GL'E. eds. *Historical Aspects of Microscopy*. (pp 3-112) Cambridge, Heffer.
- Dancer JB (1886): The introduction of photography into Liverpool and Manchester. *Manchester Courier and Lancashire General Advertiser*, May 22.
- Desaguliers JT (1716): A plain and easy experiment to confirm Sir Isaac Newton's doctrine of the different refrangibility of the rays of light. *Philosophical Transactions of the Royal Society* 34: 448-452.
- Deutsch D (1974): An auditory illusion. *Nature* 25: 307-309.
- Deutsch D (1979): Binaural integration of melodic patterns. *Perception & Psychophysics* 25: 399-405.
- Deutsch D (2004): The octave illusion revisited again. *Journal of Experimental Psychology: Human Perception and Performance* 30: 355-364.
- Dove HW (1839): Interferenz des Tones. *Repertorium der Physik* 3: 91-100.

Dove HW (1841): Die Combination der Eindrücke beider Ohren und beider Augen zu einem Eindruck. *Bericht über die zur Bekanntmachung geeigneten Verhandlungen der königlich preussischen Akademie der Wissenschaften zu Berlin* 41: 251-252.

Dove HW (1851): Beschreibung mehrerer Prismenstereoskope und eines einfachen Spiegelstereoskops. *Annalen der Physik und Chemie* 83: 183-189.

Drake S (1957): *Discoveries and Opinions of Galileo*. New York, Doubleday.

Du Tour E-F (1760): Discussion d'une question d'optique. *Académie des Sciences. Mémoires de Mathématique et de Physique Présentés par Divers Savants* 3: 514-530.

Du Verney G (1683): *Traité de l'organe de l'ouïe, contenant la structure, les usages et les maladies de toutes les parties de l'oreille*. Paris, Michallet.

Du Verney G (1737): *A Treatise of the Organ of Hearing: Containing the Structure, the Uses, and the Diseases of all Parts of the Ear*. London, Baker.

Fechner GT (1860): *Elemente der Psychophysik*. Leipzig, Breitkopf & Härtel.

Galilei G (1623): *Il Saggiatore, nel quale con bilancia esquisita e giusta...* Roma, Mascardi

Galilei G (1638): *Discorsi e dimostrazioni matematiche: intorno a due nuove scienze attenenti alla meccanica & i movimenti locali*. Leida, Elsevirii .

Goldstein EB (2010): *Sensation and Perception*. 8th ed. Belmont, CA, Wadsworth.

Gouk P (1999): *Music, Science and Natural Magic in Seventeenth-Century England*. New Haven, CT, Yale University Press.

Gouk P (2004): English theories of hearing in the seventeenth century. In: Smith MM (ed). *Hearing history: A reader*. (pp136-150). Athens, GA, University of Georgia Press.

Gregory RL (1981): The 4th dimension of 3D (2). *Perception* 10:1-4.

Grimaldi FM (1665): *Physico-Mathesis de Lumine, Coloribus, et Iride*. Bologna, Bernia.

Harris J (1775): *A Treatise of Optics: Containing Elements of the Science; in two Books*. London, White.

- Held R, Leibowitz HW, Teuber H-L (1978): *Handbook of Sensory Physiology*. New York, Springer.
- Helmholtz H (1857): Das Telestereoskop. *Annalen der Physik und Chemie* 101: 494-496.
- Helmholtz H (1867): *Handbuch der physiologischen Optik*. In: Karsten, G (ed.) *Allgemeine Encyklopädie der Physik*. Volume 9. Leipzig, Voss.
- Helmholtz H (1873): *Popular Lectures on Scientific Subjects*. Atkinson E, trans. London, Longmans, Green.
- Hering E (1862): *Beiträge zur Physiologie*. Volume 2. Leipzig, Engelmann.
- Hering E (1879): Der Raumsinn und die Bewegungen des Auges. In: L Hermann (ed.) *Handbuch der Physiologie*. Volume 3. (pp 341-601). Leipzig, Vogel.
- Hooke R (1679): *Lectiones Cutlerianae, Or a Collection of Lectures Physical, Mechanical, Geographical & Astronomical, Made Before the Royal Society on Several Occasions ... to which are Added Divers Miscellaneous Discourses*. London, John Martyn.
- Howard IP, Rogers BA (2012): *Perceiving in Depth*. Volume 2. Oxford: Oxford University Press.
- Howard IP, Wade NJ (1996): Ptolemy's contributions to the geometry of binocular vision. *Perception* 25: 1189–1202.
- Hunt FV (1978): *Origins in Acoustics: The Science of Sound from Antiquity to the Age of Newton*. New Haven, CT, Yale University Press.
- Jaeger W (1990): Die Begründung der physiologischen Optik im 17. Jahrhundert. Von Kepler (1604) bis Newton (1704). *Sterne und Weltraum* 29: 148-156.
- Julesz B (1971): *Foundations of Cyclopean Perception*. Chicago: University of Chicago Press.
- Kandel ER, Schwartz JH, Jessell TM, Siegelbaum SA, Hudspeth AJ (2013): *Principles of Neural Science*. 5th ed. New York, McGraw-Hill.

- Kemp S (1990): *Medieval Psychology*. New York, Greenwood.
- Kepler J (1604): *Ad Vitellionem Paralipomena*. Frankfurt, Marinium and Aubrii.
- Kepler J (1611): *Dioptrice*. Augsburg, Franci.
- Kircher A (1673): *Phonurgia Nova sive Conjugium Mechanico-Physicum Artis & Naturæ Paranympa Phonosophia consinnatum*. Kempten, Dreherr.
- Laennec RTH (1819): *Traité de l'Auscultation Médiante*. Paris, Chaudé.
- Le Clerc S (1679): *Discours Touchant de Point de Veue, dans lequel il es prouvé que les chose qu'on voit distinctement, ne sont veues que d'un oeil*. Paris, Jolly.
- Le Clerc S (1712): *Système de la Vision*. Paris, Delaulne.
- Leonardo da Vinci (1721): *A Treatise of Painting*. London, Senex and Taylor.
- Lindberg DC (1976): *Theories of Vision from Al-Kindi to Kepler*. Chicago, University of Chicago Press.
- Mach E (1926): *The Principles of Physical Optics. An Historical and Philosophical Treatment*. Anderson JS, Young AFS, trans. London, Methuen.
- Mayall J (1886): The microscope. Lecture II. *Journal of the Society of Arts* 34: 1007-1021.
- McManus C (2002): *Right Hand, Left Hand. The Origins of Asymmetry in Brains, Bodies, Atoms and Cultures*. Cambridge, MA, Harvard University Press.
- Mersenne M (1636): *Harmonie Universelle*. Paris, Cramoisy.
- Molyneux W (1692): *Dioptrica Nova. A Treatise of Dioptricks in two Parts*. London, Tooke.
- Müller J (1826): *Zur vergleichenden Physiologie des Gesichtssinnes des Menschen und der Thiere, nebst einen Versuch über die Bewegung der Augen und über den menschlichen Blick*. Leipzig, Cnobloch.
- Müller J (1843): *Elements of Physiology*, Vol. 2. Baly W, trans. London, Taylor and Walton.
- Newton I (1704): *Opticks: or, a Treatise of the Reflections, Refractions, Inflections and Colours of Light*. London, Smith and Walford.

- Ono H (1981): On Wells' 1792 law of visual direction. *Perception and Psychophysics* 30: 403-406.
- Park D (1997): *The Fire within the Eye. A Historical Essay on the Nature and Meaning of Light*. Princeton NJ, Princeton University Press.
- Piccolino M, Wade NJ (2014): *Galileo's Visions: Piercing the Spheres of the Heavens by Eye and Mind*. Oxford, Oxford University Press.
- Pierce AH (1901): *Studies in Auditory and Visual Space Perception*. New York, Longmans, Green.
- Porta JB (1593): *De Refractione. Optices Parte. Libri Novem*. Naples, Salviani.
- Priestley J (1772): *The History and Present State of Discoveries relating to Vision, Light, and Colours*. London, Johnson.
- Rayleigh, Lord (1876): Our perception of the direction of a source of sound. *Nature* 7: 32-33.
- Rayleigh, Lord. (1894): *The Theory of Sound*. (Volume 1, Ed. 2). London, Macmillan.
- Rayleigh, Lord (1907): On our perception of the direction of a source of sound. *London, Edinburgh, and Dublin Philosophical Magazine and Journal of Science* 13: 214 -323.
- Reid T (1764): *An Inquiry into the Human Mind, On the Principles of Common Sense*. Edinburgh, Millar, Kincaid & Bell.
- Riddell JL (1853): Notice of a binocular microscope. *American Journal of Science and Arts* 15, 68.
- Ronchi V (1970): *The Nature of Light. An Historical Survey*. Barocas V trans. London, Heinemann.
- Ross HE, Murray DJ (1978): *E. H. Weber: The Sense of Touch*. London, Academic Press.
- Russell GA (1996): The emergence of physiological optics. In: R Rashed (ed.) *Encyclopedia of the History of Arabic Science*. Volume 2. (pp 324-362). London, Routledge.
- Russell GA (2010): After Galen: late Antiquity and the Islamic world. In: S Finger, F Boller,

- KL Tyler (eds.) *Handbook of Clinical Neurology. Volume 95. History of Neurology.* (pp 61-77). Amsterdam, Elsevier.
- Sabra AI (1987): Psychology versus mathematics: Ptolemy and Alhazen on the moon illusion. In: E Grant, JE Murdoch (eds.). *Mathematics and its Application to Natural Philosophy in the Middle Ages.* (pp 217-247). Cambridge, Cambridge University Press.
- Sabra AI (1989): *The Optics of Ibn Al-Haytham. Books I-III. On Direct Vision.* London, The Warburg Institute.
- Schaaf L (1992): *Out of the Shadows. Herschel, Talbot and the Invention of Photography.* London, Yale University Press.
- Scheiner C (1619): *Oculus, hoc est fundamentum opticum....* Innsbruck, Agricola.
- Schmitz E-H (1982): *Handbuch der Geschichte der Optik. Ergänzungsband I. Das Fernrohr.* Bonn: Wayenborgh.
- Schyrleus de Rheita, AM (1645): *Oculus Enoch et Eliæ sive Radius Sideromysticus.* Antwerp, Verdussi.
- Seebeck A (1846): Beiträge zur physiologie des gehör- und gesichtssinnes. *Annalen der Physik und Chemie* 68: 449–465.
- Siegel RE (1970): *Galen on Sense Perception.* Basel, Karger.
- Smith AM (1996): *Ptolemy's Theory of Visual Perception: An English Translation of the Optics with Introduction and Commentary.* Philadelphia, The American Philosophical Society.
- Smith R (1738): *A Compleat System of Opticks in Four Books.* Cambridge, Published by the Author.
- Steinhauser A (1877): *Die Theorie des binauralen Hörens. Ein Beitrag zur Lehre vom Schalle.* Vienna, Gerold.

Steinhauser A (1879): The theory of binaural audition. A contribution to the theory of sound.

London, Edinburgh, and Dublin Philosophical Magazine and Journal of Science 7:

181–197 and 261–274.

Stratton GM (1917): *Theophrastus and the Greek Physiological Psychology before Aristotle*.

New York: Macmillan.

Stumpf C (1916): Binaurale Tonmischung, Mehrheitsschwelle und Mitteltonbildung.

Zeitschrift für Psychologie 75: 330–350.

Taylor J (1738): *Le Mechanisme ou le Nouveau Traité de l'Anatomie du globe de l'oeil, avec*

l'usage de ses différentes parties, & de celles qui lui sont contigues. Paris, David.

Thompson JS, Thompson HG (1920): *Silvanus Phillips Thompson D.Sc., LL.D., F.R.S. His*

Life and Letters. London, Fisher Unwin.

Thompson SP (1877): On binaural beats. *London, Edinburgh, and Dublin Philosophical*

Magazine and Journal of Science 4: 274–276.

Thompson SP (1878): Phenomena of binaural audition. *London, Edinburgh, and Dublin*

Philosophical Magazine and Journal of Science 6: 383–391.

Thompson SP (1879): The pseudophone. *London, Edinburgh, and Dublin Philosophical*

Magazine and Journal of Science 8: 385–390.

Thompson SP (1881): Phenomena of binaural audition.—Part III. *London, Edinburgh, and*

Dublin Philosophical Magazine and Journal of Science 12: 351–355.

Thompson SP (1882): On the function of two ears in the perception of space. *London,*

Edinburgh, and Dublin Philosophical Magazine and Journal of Science 13: 406–416.

Turner RS (1994) *In the Eye's Mind. Vision and the Helmholtz-Hering Controversy*.

Princeton: Princeton University Press.

Venturi JB (1796): Considérations sur la connaissance de l'étendue que nous donne le sens de

l'ouïe. *Magasin Encyclopédique, ou Journal des Sciences, des Lettres et des Arts* 3:

29-37.

Venturi JB (1802): Betrachtungen über die Erkenntniss der Entfernung, die wir durch das Werkzeug des Gehörs erhalten. *Archiv für die Physiologie* 5: 383–392.

Vieth GUA (1818): Ueber die Richtung der Augen. *Annalen der Physik* 28:233-253.

von Hornbostel EW, Wertheimer M (1920): Über die Wahrnehmung der Schallrichtung. *Sitzungsberichte der preussische Akademie der Wissenschaften* 20: 388–396.

Wade NJ (1981): A note on the history of binocular microscopes. *Perception* 10: 591-592.

Wade NJ (Ed.) (1983): *Brewster and Wheatstone on Vision*. London, Academic Press.

Wade NJ (1987): On the late invention of the stereoscope. *Perception* 16, 785–818.

Wade NJ (1998): *A Natural History of Vision*. Cambridge, MA, MIT Press.

Wade NJ (2003): *Destined for Distinguished Oblivion: The Scientific Vision of William Charles Wells (1757–1817)*. New York, Kluwer/Plenum.

Wade NJ (2005): Sound and sight: acoustic figures and visual phenomena. *Perception* 34: 1275-1290.

Wade NJ (2007): Galileo and the senses: vision and the art of deception. *Galileana* 4: 259-288.

Wade NJ (2016): Capturing motion and depth before cinematography. *Journal of the History of the Neurosciences* 25: 3-22.

Wade NJ, Deutsch D (2008): Binaural hearing – before and after the stethophone. *Acoustics Today* 4 (July): 16-27.

Wade NJ, Ngo T (2013): Early views on binocular rivalry. In: Miller S (Ed.) *Constitution of Visual Consciousness: Lessons from Binocular Rivalry*. Amsterdam: John Benjamins. pp. 77-108.

Wade NJ, Ono H (2005): From dichoptic to dichotic: historical contrasts between binocular vision and binaural hearing. *Perception* 34: 645-668.

- Wade NJ, Ono H (2012): Early studies of binocular and stereoscopic vision. *Japanese Psychological Research* 54: 54-70.
- Weber EH (1846): Der Tastsinn und das Gemeingefühl. In: Wagner R (Ed.) *Handwörterbuch der Physiologie* (Volume III, pp 481–588). Braunschweig: Vieweg.
- Wells WC (1792): *An Essay upon Single Vision with two Eyes: together with Experiments and Observations on several other Subjects in Optics*. London: Cadell.
- Wenham FH (1854): On the application of binocular vision to the microscope. *Transactions of the Microscopical Society of London* 2: 1-13.
- Wheatstone C (1823): New experiments on sound. *Annals of Philosophy* 6: 81–90.
- Wheatstone C (1827): Experiments on audition. *Quarterly Journal of Science, Literature and Art* 24: 67–72.
- Wheatstone C (1833): On the figures obtained by strewing sand on vibrating surfaces, commonly called acoustic figures. *Philosophical Transactions of the Royal Society* 123: 593–634.
- Wheatstone C (1838): Contributions to the physiology of vision - Part the first. On some remarkable, and hitherto unobserved, phenomena of binocular vision. *Philosophical Transactions of the Royal Society* 128: 371–394.
- Wheatstone C (1852): Contributions to the physiology of vision – Part the second. On some remarkable, and hitherto unobserved, phenomena of binocular vision. *Philosophical Transactions of the Royal Society* 142: 1–17.
- Wheatstone C (1853): On the binocular microscope, and on stereoscopic pictures of microscopic objects. *Transactions of the Microscopical Society of London* 1 99-102.
- Woolgar CM (2006): *The Senses in Late Medieval England*. New Haven, CT, Yale University Press.
- Yost WA (1997): The cocktail party problem: Forty years later. In: Gilkey RH, Anderson TR (Eds.), *Binaural and Spatial Hearing in Real and Virtual Environments*

(pp. 329-347). Mahwah, NJ: Erlbaum.

Young T (1793): Observations on vision. *Philosophical Transactions of the Royal Society* 83:169-181.

Young T (1800): Outline of experiments and enquiries respecting sound and light.
Philosophical Transactions of the Royal Society 90: 106–150.

Young T (1807): *A Course of Lectures on Natural Philosophy and the Mechanical Arts*.
London: Johnson.

Zahn J (1685): *Oculus Artificialis Teledioptricus sive Telescopium*. Würzburg: Heyl.

Zahn J (1686): *Oculo Artificiali Teledioptrico sive Telescopio, Fundamentum III. Practico-Mechanicum*. Würzburg: Heyl.

Ziggelaar A (1983): *François de Aguilón S. J. Scientist and architect*. Rome: Bibliotheca Instituti
Historici S. I.

Table 1. Comparison of pages devoted to vision and hearing in books on the senses

Book	Period	Vision	Hearing
Theophrastus (Stratton, 1917)	Early Greek	6	3
Beare (1906)	Early Greek	81	37
Galen (Siegel, 1970)	Roman	117	13
Kemp (1990)	Medieval	10	1
Woolgar (2006)	Late Medieval	43	21
Aquapendente (1600)	16 th century	133	38
Bell (1803)	18 th century	148	80
Schäfer (1900)	19 th century	122	56
Boring (1942)	Mid-20 th century	214	124
Held, et al. (1978)	Late-20 th century	580	66
Barlow & Mollon (1982)	Late-20 th century	204	93
Goldstein (2010)	20 th century	214	67
Kandel, et al. (2013)	Early 21 st century	98	57

Figure legends

Figure 1. Binocular disparities as illustrated in Aguilonius (1613, frontispiece to Book IV).

The cosmic observer fixates on the central cross (on the screen), thus producing crossed visible directions of the near object. The putti are pointing to the discs on the screen which mark the locations of the crossed directions.

Figure 2. 18th century techniques for presenting different stimuli to the two eyes. Lower left, Le Clerc's (1712) method of viewing through an aperture nearer than the targets. A similar technique was used by Desaguliers (1716) as shown in the upper figure. Du Tour (1760) placed targets on either side of a septum (lower right); he also used prisms to stimulate the eyes with different patterns.

Figure 3. Left, a diagram from Steinhauser (1879) showing the head from above and the limits of direct, mixed and indirect binaural audition. The figure shows “the aspect of the human head from above, f_1 and f_2 being the surfaces of the pinnæ. They make with one another an angle 2β ” (p. 183). Right, the arrangement of telephones in the studies described by Bell (1880). The sounds from a speaker walking around the room EFGH could be heard through C and D together or separately.

Figure 4. Upper, an engraving from Chérubin d'Orléans (1671) showing putti using mounted and hand-held binocular telescopes. Centre, a diagram of a binocular microscope (from Chérubin d'Orléans, 1677). Lower, a woodcut of a binocular microscope from Zahn (1686).

Figure 5. Left, Wheatstone's mirror stereoscope viewed from the front and above (from Wheatstone, 1838). Right, Brewster's lenticular stereoscope (from Brewster, 1856).

Figure 6. Left, Wheatstone's (1827) microphone, centre, Alison's (1859) stethophone and right, Thompson's (1879) pseudophone, all as illustrated in their original articles.

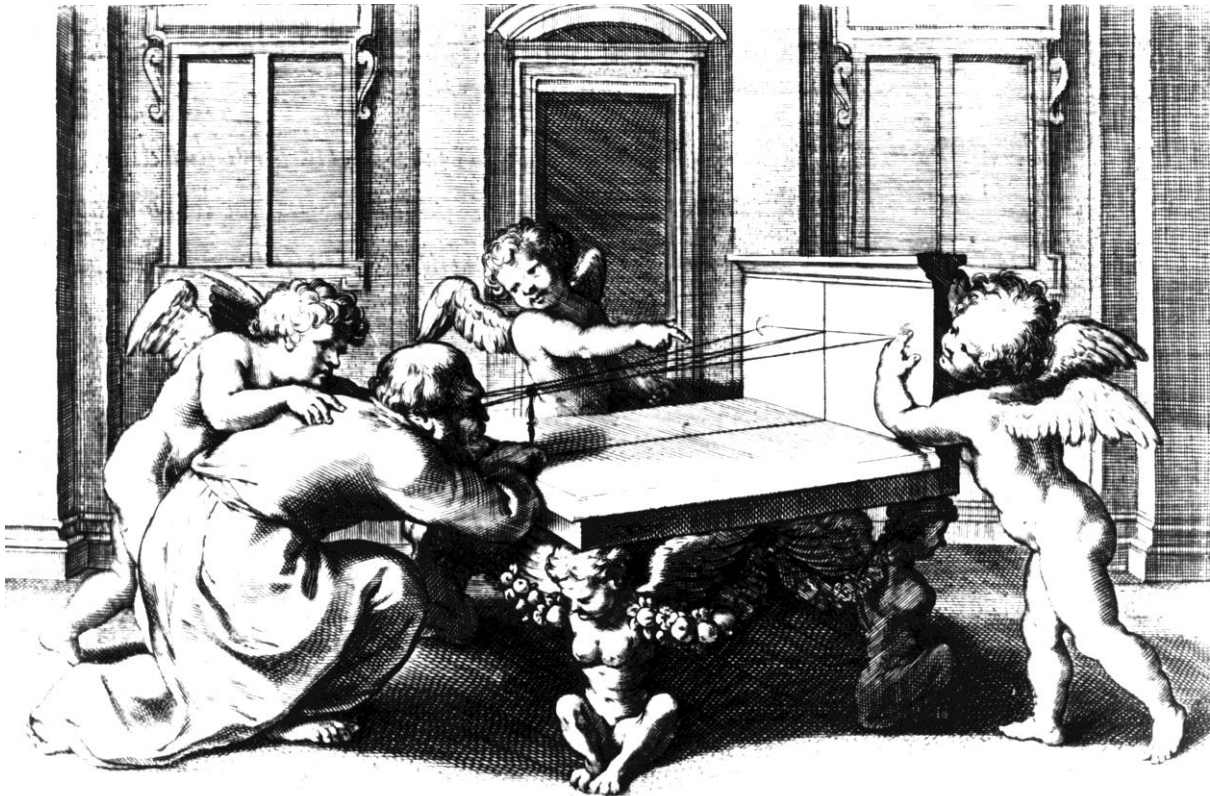


Figure 1. Binocular disparities as illustrated in Aguilonius (1613, frontispiece to Book IV).

The cosmic observer fixates on the central cross (on the screen), thus producing crossed visible directions of the near object. The putti are pointing to the discs on the screen which mark the locations of the crossed directions.

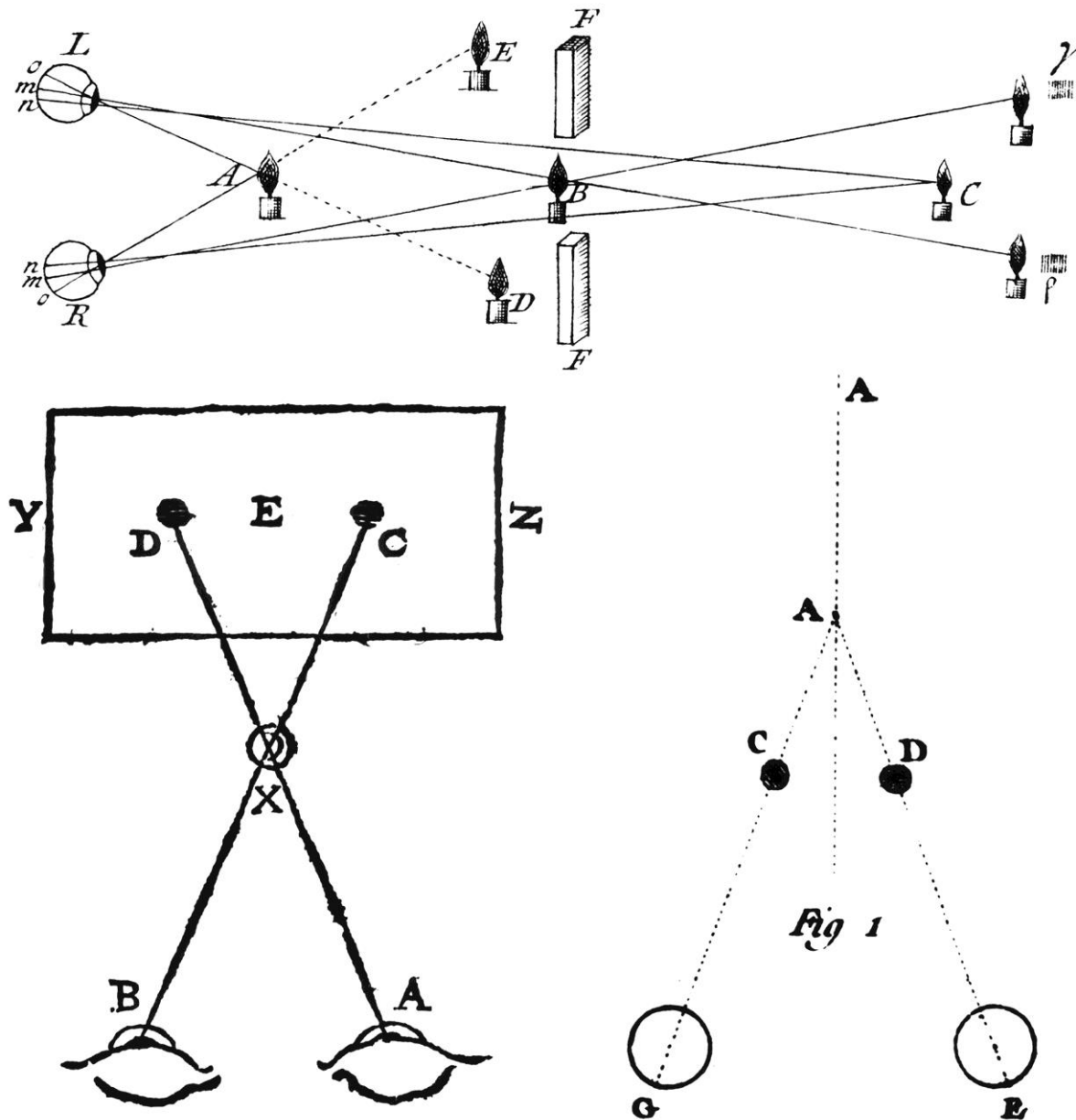


Figure 2. 18th century techniques for presenting different stimuli to the two eyes. Lower left, Le Clerc's (1712) method of viewing through an aperture nearer than the targets. A similar technique was used by Desaguliers (1716) as shown in the upper figure. Du Tour (1760) placed targets on either side of a septum (lower right); he also used prisms to stimulate the eyes with different patterns.

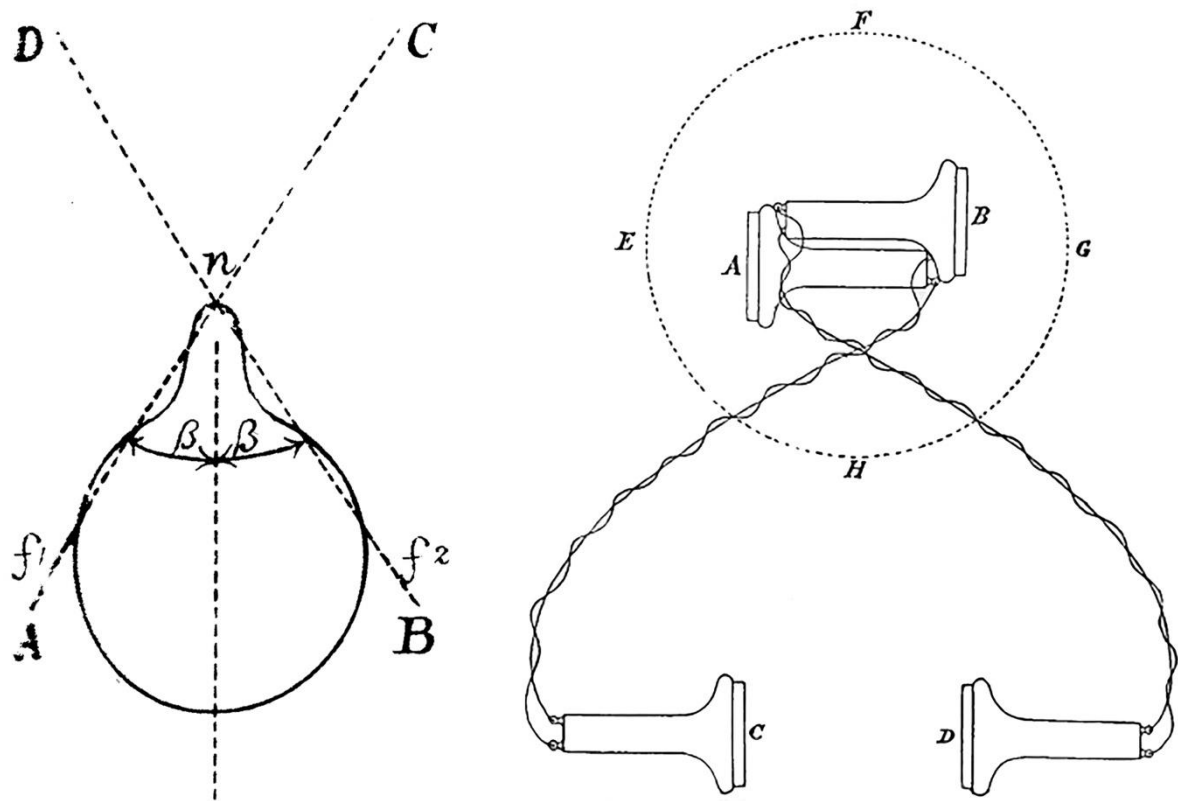


Figure 3. Left, a diagram from Steinhauser (1879) showing the head from above and the limits of direct, mixed and indirect binaural audition. The figure shows “the aspect of the human head from above, f_1 and f_2 being the surfaces of the pinnæ. They make with one another an angle 2β ” (p. 183). Right, the arrangement of telephones in the studies described by Bell (1880). The sounds from a speaker walking around the room EFGH could be heard through C and D together or separately.

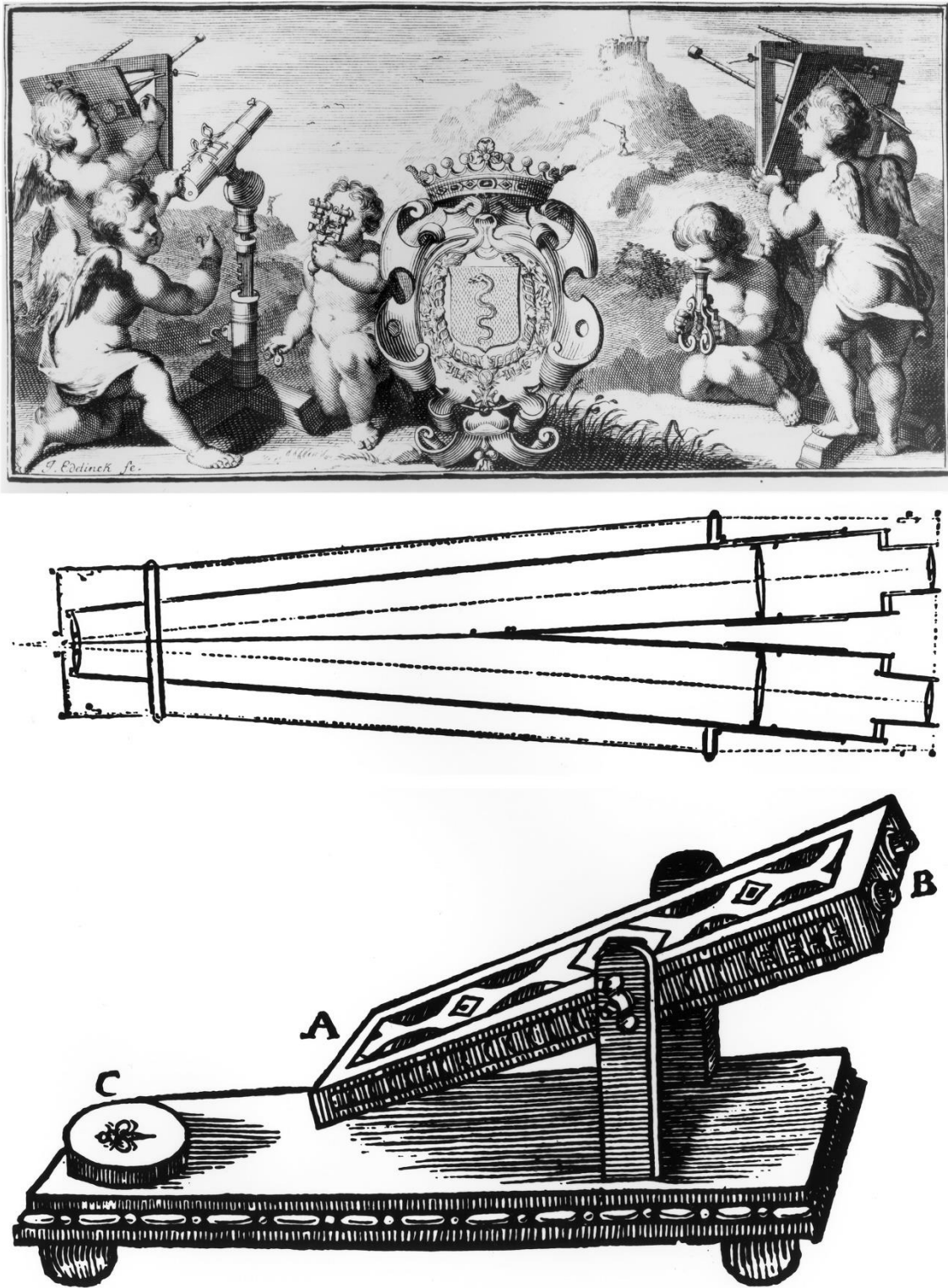


Figure 4. Upper, an engraving from Chérubin d'Orléans (1671) showing putti using mounted and hand-held binocular telescopes. Centre, a diagram of a binocular microscope (from Chérubin d'Orléans, 1677). Lower, a woodcut of a binocular microscope from Zahn (1686).

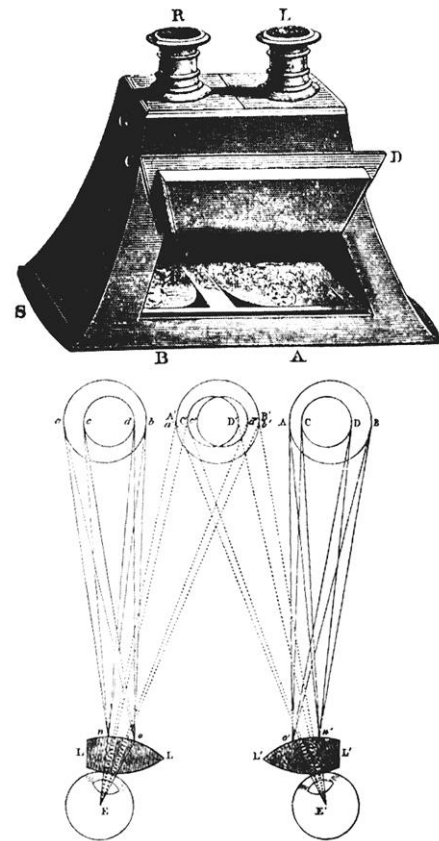
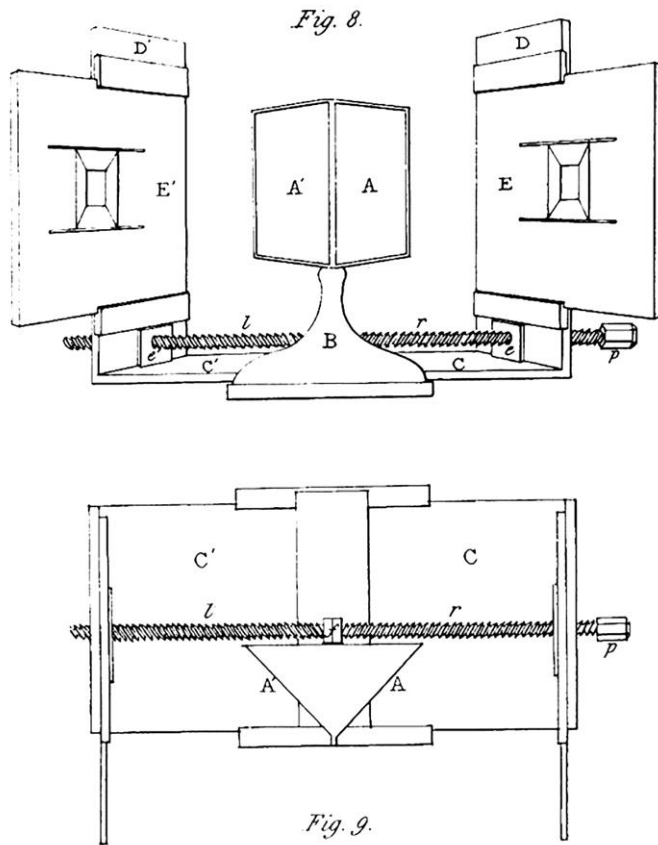


Figure 5. Left, Wheatstone's mirror stereoscope viewed from the front and above (from Wheatstone, 1838). Right, Brewster's lenticular stereoscope (from Brewster, 1856).

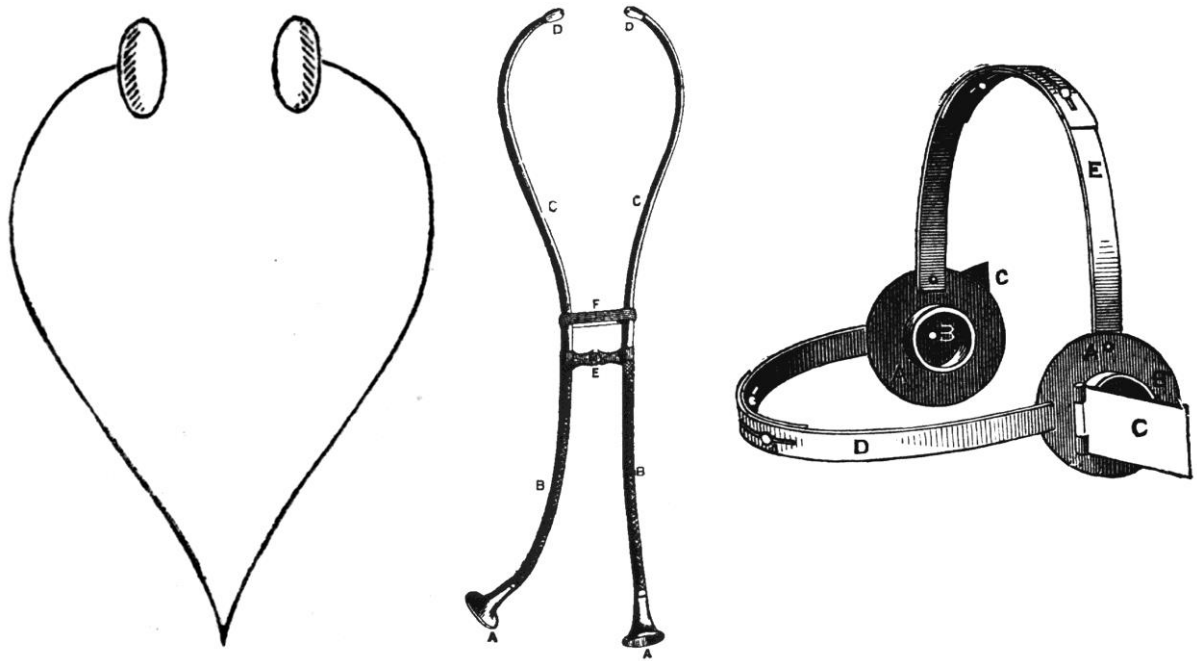


Figure 6. Left, Wheatstone's (1827) microphone, centre, Alison's (1859) stethophone and right, Thompson's (1879) pseudophone, all as illustrated in their original articles.

